# Concurrent Response Selection in Dual-Task Performance: Evidence for Adaptive Executive Control of Task Scheduling*

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## Abstract

Four experiments with the psychological refractory period (PRP) procedure are reported that investigate how people perform multiple tasks concurrently. In each experiment, a primary task was paired with a secondary task that had two levels of response-selection difficulty. Experiments 1 and 2 varied response-selection difficulty by manipulating the number of alternative stimulus-response (S-R) pairs in the secondary task. In both experiments, the effect of this factor on secondary-task reaction times (RTs) decreased reliably as the stimulus onset asynchrony (SOA) decreased. Experiments 3 and 4 varied response-selection difficulty by manipulating S-R compatibility for the secondary task. Again, the effect of this factor on secondary-task RTs decreased reliably as SOA decreased, regardless of whether or not the primary and secondary tasks involved the same response modality. Taken together, these results raise doubts about the existence of an immutable structural central bottleneck in response selection. Rather, it appears that response-selection processes for two concurrent tasks may temporally overlap. This outcome is consistent with dual-task performance models (Meyer & Kieras, 1997a, 1997b, 1997c; Meyer et al., 1995) under which people have adaptive executive control of their task-scheduling strategies.

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## Introduction

The psychological refractory period (PRP) procedure has been used extensively to investigate human dual-task performance (for reviews, see Meyer & Kieras, 1997a, 1997b; Pashler, 1994a). In this procedure, participants must respond to two successively presented stimuli on each trial. The time between the first and second stimulus is the stimulus onset asynchrony (SOA). Participants are typically instructed to respond quickly and accurately to both stimuli, but to give primary emphasis to the first one. Reaction times (RTs) for the second stimulus typically increase as SOA decreases (the PRP effect), whereas SOA has little or no effect on RTs for the first stimulus.

Many theories have been proposed to explain the PRP effect, of which the most prominent is the response-selection bottleneck (RSB) hypothesis (Pashler, 1984; Pashler, 1994a; Welford, 1980). According to the RSB hypothesis, performing each task in the PRP procedure requires a series of processing stages, including a response-selection stage that only can deal with one task at a time. The RSB hypothesis therefore implies that when the SOA is short and the response-selection stage is devoted to the primary task, the secondary task must wait temporarily, causing the PRP effect.

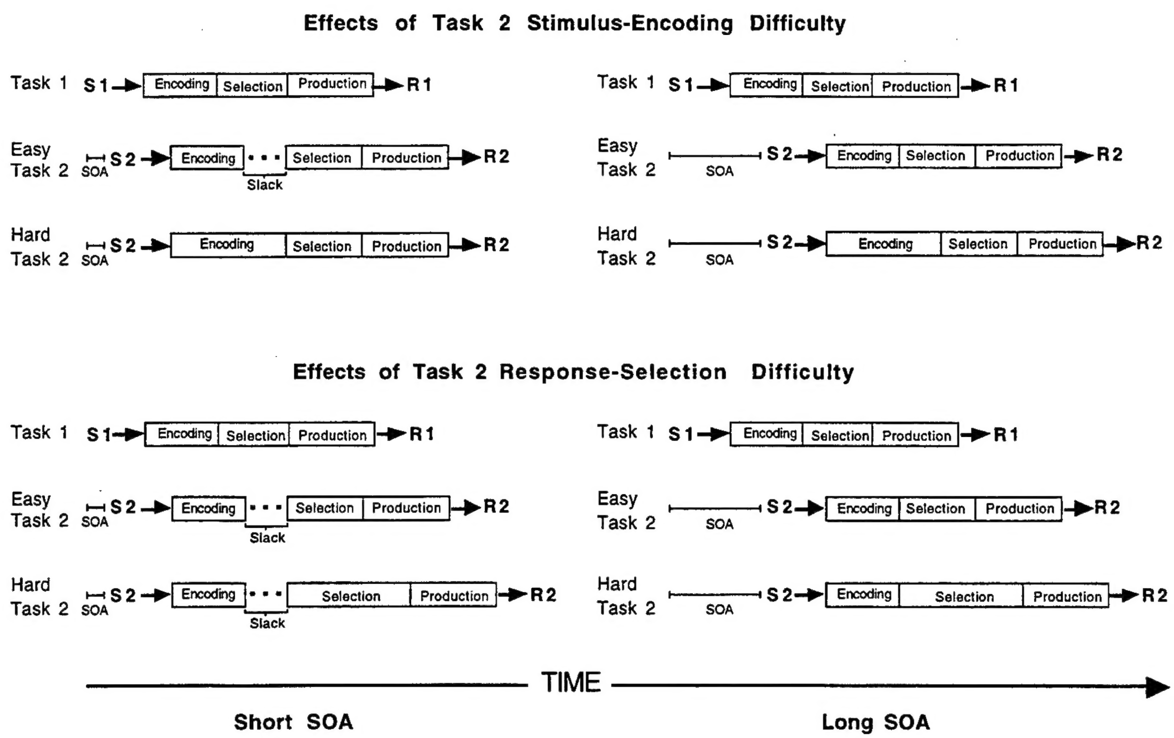


*Figure 1*. Timeline for stages of processing according to the response-selection bottleneck hypothesis under the psychological refractory period procedure. Processing for Task 1 and Task 2 begins with the presentation of a task stimulus (S), continues through stimulus encoding, response selection, and movement production, ending with the output of an overt response (R). The upper half of the figure shows how manipulations of Task 2 stimulus-encoding difficulty and SOA produce underadditive effects on Task 2 RTs. The lower half of the figure shows how manipulations of Task 2 response-selection difficulty and SOA produce additive effects on Task 2 RTs.

To test the RSB hypothesis, some researchers have manipulated secondary-task factors that affect different processing stages, and have used *locus-of-slack logic* to interpret their results (De Jong, 1993; Fagot & Pashler, 1992; McCann & Johnston, 1992; Pashler, 1984; Pashler & Johnston 1989; Ruthruff, Miller, & Lachmann, 1995). For example, manipulations of SOA and Task 2 stimulus intensity, which affects secondary-task stimulus encoding, have been found to produce underadditive effects on mean Task 2 RTs (De Jong, 1993; Pashler, 1984; Pashler & Johnston 1989). In contrast, manipulations of SOA and Task 2 factors such as stimulus repetition (Pashler & Johnston, 1989), memory-retrieval difficulty (Carrier & Pashler, 1995), target presence/absence (Pashler, 1984), mental-rotation angle (Ruthruff, Miller, & Lachmann, 1995), and stimulus-response (S-R) compatibility (Fagot & Pashler, 1992; McCann & Johnston, 1992), all of which affect secondary-task response selection, have been found to produce additive effects on mean Task 2 RTs. As Figure 1 shows, this pattern of RT effects could stem from a bottleneck in response selection. At short SOAs, the bottleneck allows effects on Task 2 processing stages before, but not after, the bottleneck to be absorbed in the processing slack that occurs while Task 2 waits for the completion of Task 1 response selection.

Yet the exact nature of the response-selection bottleneck remains unclear. Pashler (1984; 1994a; 1994b) and others (e.g., De Jong, 1993; McCann & Johnston, 1992; Pashler & Johnston, 1989; Welford, 1980) have proposed that it is an immutable structural central mechanism. According to this proposal, the human brain is "wired" such that it only can select the response to one stimulus at a time. If this is true, then manipulations of SOA and Task 2 response-selection difficulty should always have additive effects on mean Task 2 RTs during the PRP procedure. However, some studies have yielded underadditive effects of these factors (De Jong, 1993; Hawkins, Rodriquez, & Reicher, 1979; Ivry, Franz, Kingstone, & Johnston, 1996; Karlin & Kestenbaum, 1968; Meyer et al., 1995). For example, Figure 2 shows mean Task 2 RTs from studies by (A) Karlin and Kestenbaum (1968) and (B) Hawkins et al. (1979) in which Task 2

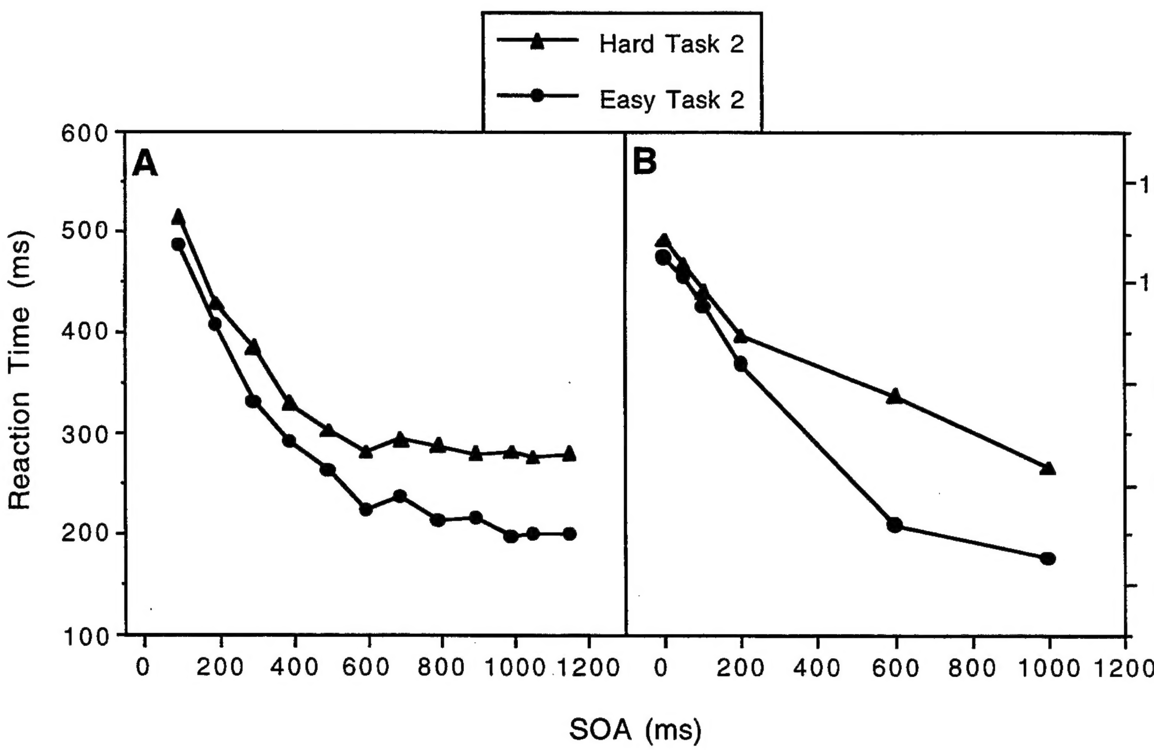


***Figure 2***. Mean Task 2 RTs as a function of Task 2 response-selection difficulty and SOA in PRP studies by (A) Karlin and Kestenbaum (1968) and (B) Hawkins et al. (1979).

response-selection difficulty was manipulated by varying the number of alternative S-R pairs. These studies suggest that in some situations, the bottleneck may occur after the response-selection stage, and people may select the responses for two tasks concurrently, contrary to the RSB hypothesis (Keele, 1973; Meyer & Kieras, 1997a).

Given such considerations, Meyer and Kieras (1997a, 1997b, 1997c; Meyer et al., 1995) have formulated an alternative account of dual-task performance in the PRP procedure. They propose a class of adaptive executive-control (AEC) models whereby people have flexible control over the course of secondary-task processing. AEC models assume that such control is achieved through executive processes whose operations can lock out (suspend) and unlock (resume) Task 2 between any two processing stages (Figure 3).

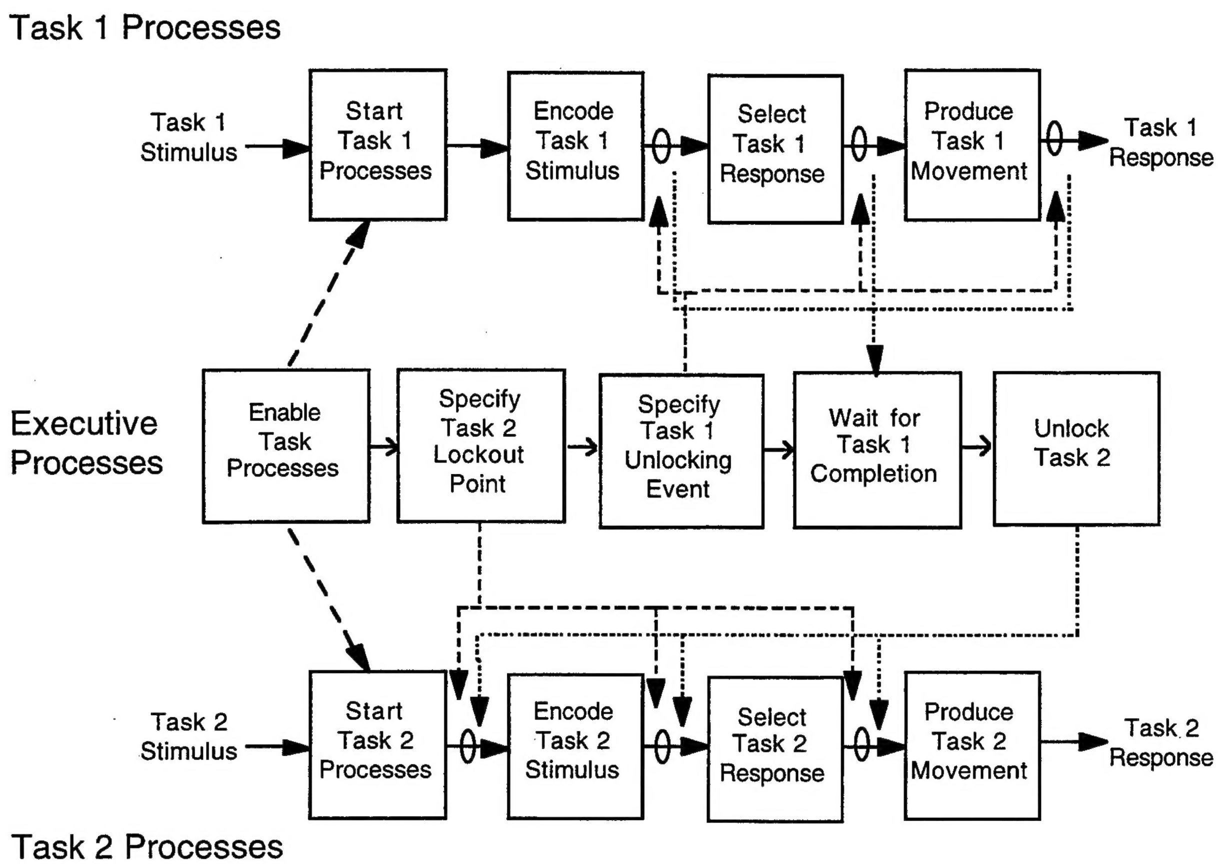


*Figure 3*. Component processes for adaptive executive-control (AEC) models whereby tasks in the psychological refractory period procedure may be flexibly scheduled. Arrows leading to and from various executive processes denote where a Task 2 lockout point may be set, where a Task 1 unlocking event may occur, where Task 1 processing is deemed to be completed, and where Task 2 processing should be resumed.

According to this view, the *Task 2 lockout point* is a stage of processing in the course of Task 2 such that when it is about to start, further progress on Task 2 is suspended temporarily until Task 1 is deemed to be completed. The *Task 1 unlocking event* is a stage of processing in the course of Task 1 such that when it has ended, Task 1 is deemed to be completed. When the Task 1 unlocking event occurs, executive processes unlock Task 2 and let the secondary-task stages proceed to completion from the point at which they were previously suspended. Like the choice of a decision criterion (beta) in signal-detection theory (Tanner & Swets, 1954), the specifications of

particular Task 2 lockout points and Task 1 unlocking events by the executive processes are presumably optional. With these specifications, executive processes may implement various alternative "software" bottlenecks and scheduling strategies, depending on relative task priorities, participants' strategic biases or degree of practice, and other ancillary factors. The location of the lockout point in Task 2 and unlocking event in Task 1 determine particular subtypes of AEC models.

Under some conditions, the emphasis on Task 1 in the PRP procedure may lead participants to adopt a response-selection bottleneck scheduling strategy, producing a strategic rather than structural bottleneck. That is, optionally locking out Task 2 before secondary-task response selection and waiting to unlock it until after completion of primary-task response selection would create a strategic response-selection bottleneck.

Additionally, because of the flexibility that people presumably have in determining the suspension and resumption of secondary-task processing, AEC models predict that dual-task performance can change with practice, as participants develop more optimal ways of scheduling the processes for the two tasks. For example, suppose that the primary or secondary tasks in a dual-task situation are particularly difficult. Then people may begin performing the tasks with a conservative scheduling strategy that uses a software response-selection bottleneck. However, after practice, they may adopt a more daring scheduling strategy that has overlapping response-selection processes. Such a practice effect would be achieved by shifting from an early (pre-response selection) to late (post-response selection) Task 2 lockout point.

Here we report four experiments whose results provide further evidence that response-selection bottlenecks are optional and strategic rather than structural and immutable, thereby extending the task situations where overlapping response selection has been found. Our experiments also examine the effect of practice on participants' choice of task-scheduling strategies, which is an important aspect of dual-task performance that has not yet received sufficient investigation (Gopher, 1993). Experiment 1 replicates and extends prior work by Karlin and Kestenbaum (1968) using S-R numerosity to manipulate response-selection difficulty in an auditory-manual secondary task. We, like Karlin and Kestenbaum (1968), find an underadditive interaction between the effects of this factor and SOA on mean Task 2 RTs. To decrease the likelihood that this response-selection manipulation also affected the difficulty of stimulus encoding, Experiment 2 replicates and extends prior work by Hawkins et al. (1979) with symbolic stimuli (viz., digits) instead of tones as the Task 2 stimuli. Again we, like Hawkins et al. (1979), find an underadditive interaction between the effects of this factor and SOA on mean Task 2 RTs for similar tasks. Experiment 3, which replicates and extends prior work by McCann and Johnston (1992), manipulates another popular response-selection factor (viz., S-R compatibility). The results of Experiment 3 reveal that participants' task-scheduling strategies change with practice. Early in training, participants show evidence of a cautious scheduling strategy with a strategic response-selection bottleneck, but after practice, they come to use a daring scheduling strategy that overlaps response-selection processes for the two tasks. Finally, Experiment 4 replicates Experiment 3 using different response modalities for the two tasks. The results from Experiment 4 rule out the possibility that the previous underadditive interactions stemmed from a secondary immutable structural bottleneck in movement production.

## Experiment 1

Task 1 in this experiment was a two-choice visual-manual task. Task 2 was an auditory-manual task for which the correct responses were determined by the frequencies of presented tones. We used an auditory-manual secondary task because it did not require eye movements to encode the Task 2 stimuli, which can preclude response-selection processes for Tasks 1 and 2 from temporally overlapping (cf. McCann & Johnston, 1992; Meyer & Kieras, 1997a, 1997b). Task 2 response-selection difficulty was manipulated by varying S-R numerosity. This manipulation is appropriate because prior research has shown that S-R numerosity mainly affects response selection (Brainard, Irby, Fitts, & Alluisi, 1962; Broadbent & Gregory, 1965; Fitts, Peterson, & Wolpe, 1963; Gottsdanker, 1969; Keele, 1973; Sternberg, 1969; Theios, 1973).

Additionally, we kept the number of manual responses constant across the levels of Task 2 response-selection difficulty to preclude any ancillary effects of response modality on movement production (Miller & Ulrich, 1996).

As stated previously, Karlin and Kestenbaum (1968) found a large underadditive interaction between the effects of S-R numerosity and SOA on mean Task 2 RTs for similar tasks. Their S-R numerosity effect was 81 ms at the longest SOA but only 27 ms at the shortest SOA (Figure 2A). By locus-of-slack logic, this underadditivity implies that response-selection processes for the two tasks occurred concurrently.

However, Karlin and Kestenbaum's (1968) easy and hard levels of response-selection difficulty involved simple-RT and choice-RT tasks, respectively. This complicates the interpretation of their results. Pashler (1994a) has argued that RTs for simple-RT and choice-RT tasks cannot be compared validly because "PRP effects observed in simple RT seem fundamentally different from those found in choice RT tasks" (p. 229). Although he did not specify exactly what these "fundamental" differences might be or how they would obviate the results of Karlin and Kestenbaum, we take Pashler's concern seriously, nevertheless. Therefore, to disarm this concern, both levels of Task 2 response-selection difficulty in Experiment 1 involve choice-RT tasks.

## *Method*

### *Participants*

Eleven right-handed undergraduate students (5 males and 6 females) from the University of Michigan participated in this study as paid volunteers. They had normal or corrected to normal vision, and were paid $5.00/hour plus a bonus based on the quality of their performance. The data from three participants were not analyzed because two of them (1 male and 1 female) had error rates greater than 15% and the other (female) did not learn the tasks quickly enough (so N = 8 in the analyses).

### *Apparatus*

Participants sat about 80 cm from a display screen in a quiet, semi-dark room. Visual stimuli were presented on a Zenith ZVM-1200 monochrome monitor, using an AST Premium 386 personal computer. Auditory stimuli were presented over Sennheiser HMD 24 headphones. Responses were made with a piano-type response keyboard. It had two groups of five finger keys, with one group for each hand.

### *Design and Procedure*

***Tasks***. Participants performed two tasks in this experiment. Task 1 was a visual-manual task. On each trial of it, either a *2* or a *3* appeared in the center of the display monitor. Participants responded by pressing the left index-finger key for the *2* or the left middle-finger key for the *3*. Task 2 was an auditory-manual task. On each trial of it, one of four tones (330, 500, 1120, or 1650 Hz) was presented. If the 500 Hz or 1120 Hz tone sounded, participants had to press the right index-finger key. If the 330 Hz or 1650 Hz tone sounded, participants had to press the right middle-finger key. Task 2 had two (easy and hard) levels of response-selection difficulty. The hard Task 2 used all four possible S-R pairs, whereas the easy Task 2 used only two S-R pairs (viz., those with the 1120 Hz and 1650 Hz tones). The stimuli for the two tasks were separated by one of five SOAs: 50, 150, 250, 500, or 1000 ms.

***Sessions***. The experiment included two sessions. Session 1 had 18 trial blocks. Six of these were single-task blocks in which only one task was performed: two blocks for Task 1, and two for each level of Task 2 difficulty. The other 12 blocks were dual-task blocks (i.e., Task 1 was paired with either the easy or the hard Task 2 on each trial). Session 2 also had 18 trial blocks, all of which were dual-task blocks. The first two dual-task blocks of each session involved the easy and hard Task 2, respectively. On all trials during these two blocks, the two task stimuli were separated by the 500-ms SOA. All other dual-task blocks used all five SOAs. The third and fourth dual-task blocks of Session 1 involved the easy and hard Task 2, respectively,

using all five SOAs on each block. During the remainder of each session, the trial blocks were paired such that for each block pair, either the easy or hard Task 2 had to be performed, and the difficulty of Task 2 alternated across block pairs. The serial order of the easy and hard secondary tasks was counterbalanced across participants. The first two blocks of Session 2 and all of Session 1 were considered to be practice and not included in subsequent data analyses.

***Trial blocks***. All possible digit-tone-SOA combinations occurred equally often within each trial block. Each single-task block had 24 trials, and each dual-task block had 40 trials. Participants were told at the beginning of each trial block which task(s) would be involved.

***Trials***. Each trial of each block began with a fixation cross presented in the center of the display monitor. On dual-task trials, 500 ms after the onset of the fixation cross, a Task 1 digit replaced the cross, and after the SOA, a Task 2 tone sounded for 40 ms. On single-task trials, only one task stimulus was presented. The serial order of task-stimulus types and SOAs were randomized within each trial block.

***Feedback***. On each trial, participants received points for correct responses and lost points for incorrect responses. Their bonus depended on their accumulated points. We awarded 100 points per trial, minus 1 point for every 10 ms taken to respond to a particular task stimulus. We charged 100 points for every incorrect response. On dual-task blocks, participants had to respond to the digit first or else both responses were considered incorrect.[1] Additionally, participants received an extra 1000 points for each dual-task block on which their mean Task 1 RT at the 50-ms SOA was within 75 ms of their mean Task 1 RT at the 1000-ms SOA. This reward system encouraged participants to complete Task 1 as quickly as possible regardless of the SOA and discouraged grouping of Task 1 and Task 2 responses. Participants earned a dollar for every 30,000 points they scored and were fully informed about the reward system before the experiment began.

After each trial block, participants received more detailed feedback about their number of correct responses, mean RTs, and points. Also, during the first six blocks of Session 1 and the first two blocks in Session 2, participants received feedback about response accuracy and points after each trial. Subsequently, participants received this feedback only after trials for which there were incorrect responses.

## *Results*

Results of dual-task trials that had two correct responses were analyzed separately from results of trials on which errors occurred. Additionally, RT outliers in the data set for correct responses were removed using a systematic algorithm.[2] This algorithm, which precluded potential distortions by RT outliers, removed 4.5% of the trials in the overall RT data set, leaving 6,821 response pairs. The clean RT data were analyzed separately for Task 1 and Task 2 using a within-subjects ANOVA with Task 2 response-selection difficulty and SOA as factors. Figure 4 shows the mean RTs for each task as a function of Task 2 response-selection difficulty and SOA.

[1] Out-of-order errors occurred on less than 0.10% of trials overall.

[2] Most popular outlier-removal procedures suffer from one or more of several deficiencies: (a) ignoring the mean of the data set; (b) ignoring the distribution of the data set; and (c) using outliers in computing the mean and standard deviation for the data set. We therefore use an outlier-removal procedure that overcomes these deficiencies. Here the RT data were first sorted into cells defined by particular combinations of the experimental factors. Second, after this sorting, the logarithm of each correct-response RT in each cell of the experimental design was computed. This yielded transformed observations whose distributions more closely approximated Gaussian ones. Third, 10% of the logarithmetically transformed RTs from each cell's distribution tails were temporarily disregarded (trimmed). This precluded possible outliers from contributing to estimates of the standard deviations for the RT distributions in the design cells. Fourth, the means and standard deviations of the remaining RT logarithms were estimated for each cell. Fifth, each of these standard deviations was multiplied by an adjustment factor of 1.512 to compensate for the tails that had been trimmed. This yielded standard-deviation estimates for the distributions of RT logarithms in the various cells that were presumably unbiased by the presence of outliers. Sixth, RTs whose logarithms differed by more than 3.896 adjusted standard deviations from their respective trimmed means were then removed from each cell, leaving the remaining data that contributed to the reported analyses.

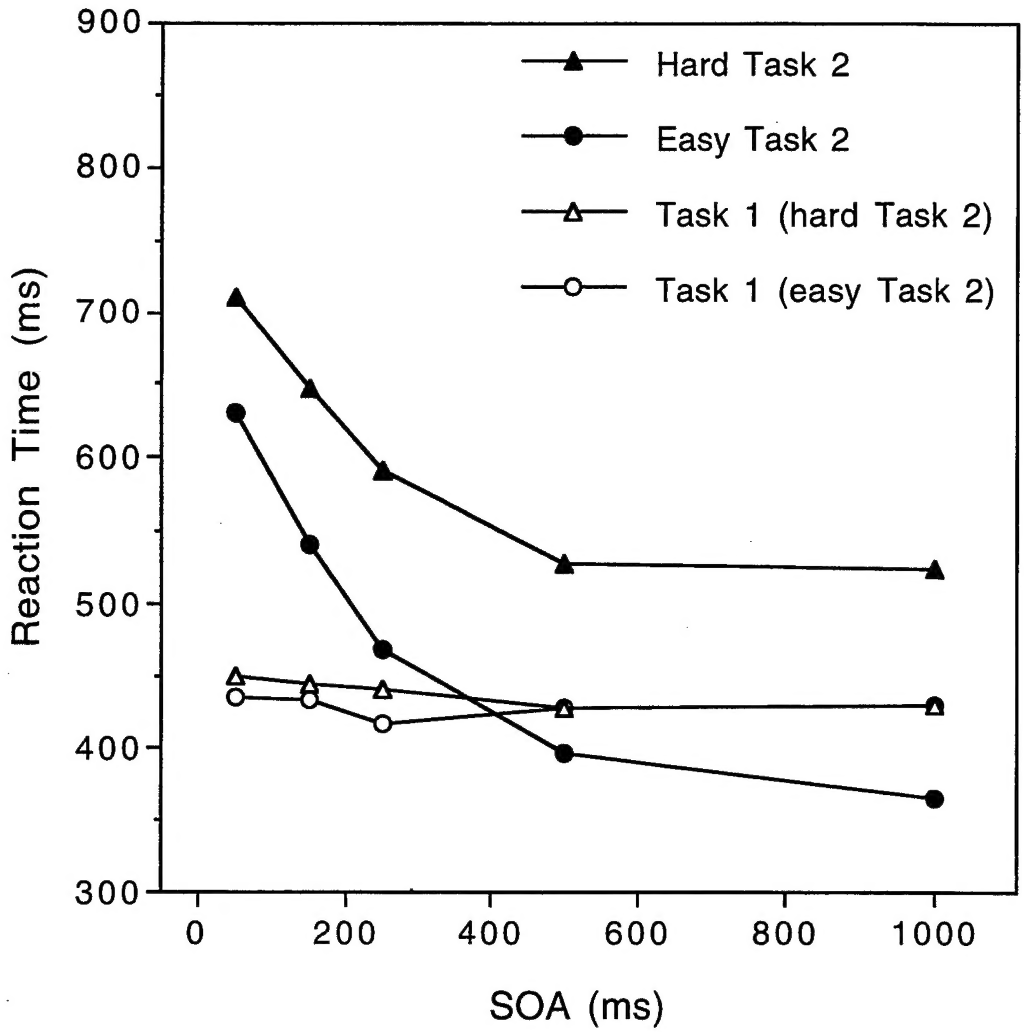


***Figure 4.*** Mean RTs for Tasks 1 and 2 as a function of Task 2 response-selection difficulty and SOA in Experiment 1.

Task 1 error rates were computed without regard for Task 2 performance and were analyzed through an ANOVA with Task 2 response-selection difficulty and SOA as factors. Task 2 error rates were analyzed separately through a similar ANOVA. Only Task 2 errors that occurred after correct Task 1 responses were analyzed. Table 1 shows the error rates for each task as a function of Task 2 difficulty and SOA. In what follows, we discuss the results more fully for each task.

### *Task 1*

***Reaction times.*** The main effect of Task 2 response-selection difficulty on mean Task 1 RTs was marginally reliable; $F(1,7) = 5.34$, $.05 < p < .06$. Mean Task 1 RTs were longer when participants performed the hard Task 2 than when they performed the easy Task 2. However, this RT difference was very small (less than 10 ms on average). Neither the main effect of SOA [$F(1,7) = 1.85$; $p > .10$] nor the interaction between the effects of Task 2 difficulty and SOA [$F(4,28) = 2.23$; $p > .05$] was reliable.

**Table 1**

***Mean Percent Errors in Experiment 1 for Each Task as a Function of Task 2 Response-Selection Difficulty and SOA***

| | SOA (ms) | | | | |
|---|---|---|---|---|---|
| Task 2 Type | 50 | 150 | 250 | 500 | 1000 |
| | | Task 1 Error Rates | | | |
| Hard | 5.85 | 7.06 | 7.81 | 7.04 | 6.64 |
| Easy | 7.99 | 4.50 | 2.70 | 3.09 | 1.75 |
| | | Task 2 Error Rates | | | |
| Hard | 1.54 | 0.00 | 0.60 | 0.60 | 0.79 |
| Easy | 1.93 | 1.96 | 0.20 | 0.75 | 1.56 |

***Error rates***. The overall error rate for Task 1 was 5.44%. The Task 2 difficulty effect on Task 1 error rate was small but reliable, $F(1,7) = 12.07$, $p < .05$. Participants made more errors on Task 1 when Task 2 was hard (6.88%) than when Task 2 was easy (4.01%). The accompanying SOA effect was not reliable, $F(4,28) = 2.53$, $p > .05$, but the interaction between the effects of Task 2 difficulty and SOA was reliable, $F(4,28) = 4.10$, $p < .01$. As SOA decreased, the number of errors on Task 1 tended to increase when Task 2 was easy, but did not change much when Task 2 was hard.

### *Task 2*

***Reaction times***. For mean Task 2 RTs, main effects of Task 2 response-selection difficulty and SOA, as well as their interaction, were reliable. Overall, mean Task 2 RTs were faster when Task 2 was easy than when Task 2 was hard, $F(1,7) = 134.96$, $p < .0005$. As the SOA decreased, mean Task 2 RTs increased, $F(4,28) = 107.45$, $p < .0005$ (Figure 4). However, the Task 2 difficulty effect decreased as SOA decreased, $F(4,28) = 5.67$, $p < .005$.[3] Figure 5 shows the response-selection difficulty effects on mean Task 2 RTs at the shortest and longest SOAs. The 79-ms difference between the Task 2 difficulty effects at these SOAs was reliable, $t(7) = 3.82$, $p < .01$.

***Error rates***. The overall Task 2 error rate was very low (0.99%). There were no reliable main effects; $F(1,7) = 2.33$, $p > .15$, and $F(4,28) = 2.18$, $p > .05$ for Task 2 difficulty and SOA, respectively. The interaction between the effects of Task 2 difficulty and SOA was small but reliable, $F(4,28) = 2.86$, $p < .05$. SOA had a slightly greater effect on error rates for the easy Task 2 than for the hard Task 2, but the error rates were less than 2% in all cases.

[3] In each of our four experiments, the interactions between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs found to be reliable in analyses of the clean data sets were also found to be reliable in analyses of the original data sets.

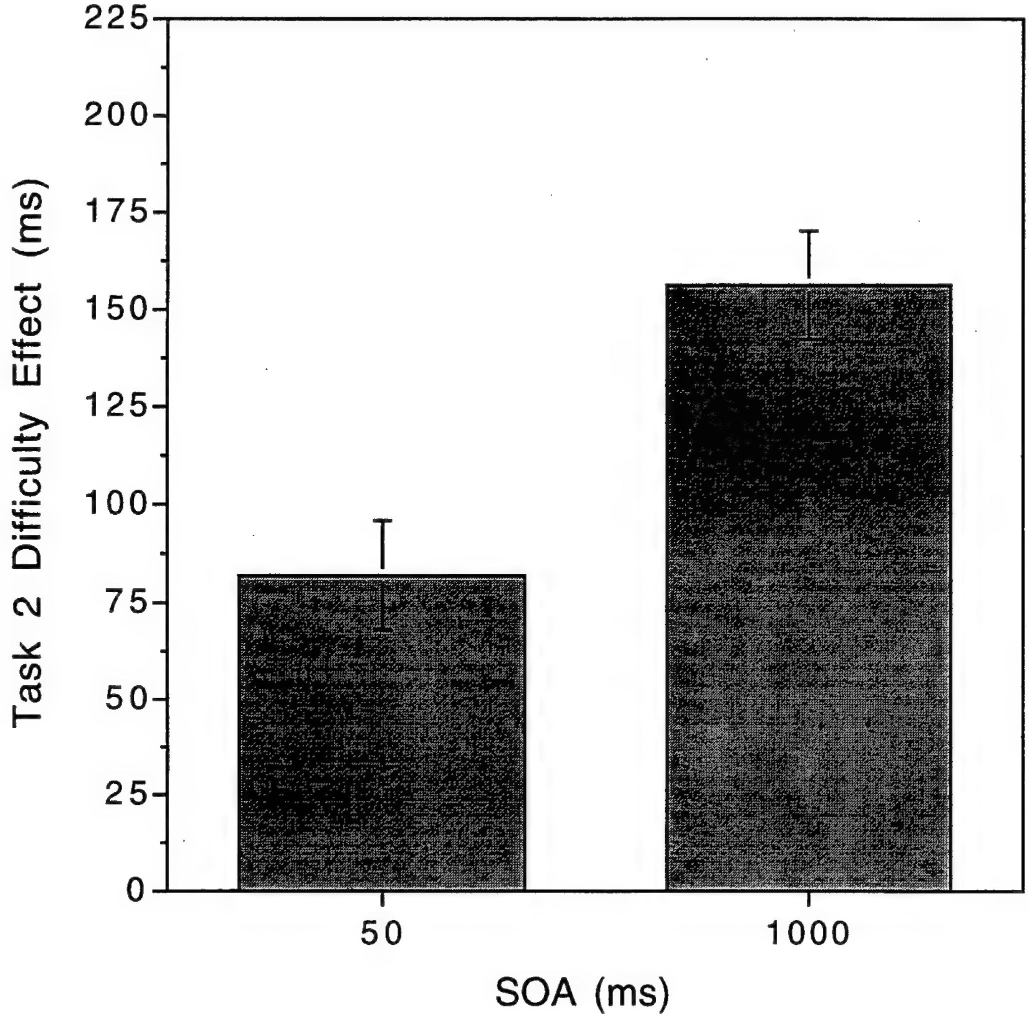


***Figure 5***. Response-selection difficulty effects and standard-error bars for mean Task 2 RTs at the shortest and longest SOAs in Experiment 1. Standard-error bars were derived from the mean squared error of the F-test for determining the reliability of the difference between the heights of the bars.

### *Discussion*

The underadditive interaction between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs is problematic for the RSB hypothesis. The difficulty effect is 79 ms less at the shortest SOA than at the longest SOA (Figure 5). This strongly suggests that response-selection processes for Tasks 1 and 2 overlapped temporally at the short SOAs. Consistent with the AEC models of Meyer and Kieras (1997a, 1997b; Meyer et al., 1995), it appears that response-selection bottlenecks may not be immutable or structural, but instead are optional and strategic.[4]

Experiment 1 substantially extends the results reported by Karlin and Kestenbaum (1968). The similarity between our results and theirs suggests that, contrary to Pashler (1994a), mean RTs from simple-RT and choice-RT tasks can be compared, at least with regard to the effects of Task 2

[4] The effects of Task 2 response-selection difficulty and SOA on Task 1 error rates complicates the interpretation of this interaction for Task 2 RTs. However, such complications did not occur in any of the other experiments and therefore cannot be used to discount the Task 2 RT data.

response-selection difficulty on mean RTs in the PRP procedure. Thus, the underadditivity reported by Karlin and Kestenbaum (Figure 2A) most likely stemmed from overlapping response-selection processes.

Yet there is one conceivable alternative explanation for the underadditive effects found in Experiment 1 and in Karlin and Kestenbaum (1968). The response-selection difficulty manipulation used there may have affected the difficulty of stimulus encoding as well as response selection. If so, then the RSB hypothesis also can explain the underadditive interaction between the effects of S-R numerosity and SOA on mean Task 2 RTs. According to this explanation, in Experiment 1 for example, participants may have discriminated an 1120 Hz tone from a 1650 Hz tone more quickly when the tones were presented as one of two alternatives rather than as one of four.

It seems unlikely to us that such a discriminability effect could account for all, or even most, of the underadditive interaction found in Experiment 1. Nevertheless, Experiment 2 addresses this possibility by changing the Task 2 stimuli from tones to printed digits. The familiarity and discrete symbolic nature of digits further reduces the likelihood that manipulations of S-R numerosity involving digits would affect stimulus-encoding rather than response-selection difficulty. Prior research has shown that effects of S-R numerosity interact strongly with effects of other response-selection manipulations, suggesting by additive-factor logic (Sternberg, 1969) that S-R numerosity also mainly affects response selection (Brainard et al., 1962; Broadbent & Gregory, 1965; Fitts, Peterson, & Wolpe, 1963; Sternberg, 1969; Theios, 1973).

Another interesting result from Experiment 1 was that a smaller interaction between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs occurred in Session 1 (47 ms) than in Session 2. On the basis of this result, one might infer that participants develop more efficient task-scheduling strategies as they become better at performing the experimental tasks. Unfortunately, Session 1 did not yield enough data to draw this conclusion definitively. Thus, to further investigate the effect of practice on task scheduling, we add a third session of dual-task performance in Experiment 2.

## Experiment 2

Task 1 of this experiment was a two-choice auditory-manual task. Task 2 was a visual-manual task in which the correct responses were associated with the identities of presented digits. Response-selection difficulty for Task 2 was manipulated by varying S-R numerosity.

Our experimental design was inspired by previous research of Hawkins et al. (1979). Using tasks similar to ours they found a large underadditive interaction between the effects of S-R numerosity and SOA on Task 2 RTs. Their S-R numerosity effect was 180 ms at the longest SOA but only 35 ms at the shortest SOA (Figure 2B). Assuming that this effect occurred during Task 2 response selection, then under the locus-of-slack logic, its interaction with SOA implies that response-selection processes for Tasks 1 and 2 overlapped temporally at the short SOAs.

In Experiment 2, we used two versions of a choice-RT task with visual stimulus digits and manual responses to vary Task 2 response-selection difficulty. Our approach addresses two possible alternate explanations that have been offered to account for the underadditive interaction between the effects of Task 2 difficulty and SOA on Task 2 RTs found by Karlin and Kestenbaum (1968). Because both levels of Task 2 difficulty involve choice-RT tasks, comparing simple and choice-RT tasks is not an issue here, and because the Task 2 stimuli are digits, there is unlikely to be much, if any, effect of S-R numerosity on stimulus encoding.

## *Method*

### *Participants*

Ten right-handed undergraduate students (8 males and 2 females) from the University of Michigan participated in this study as paid volunteers. They came from the same population as those in Experiment 1 but had not been tested previously. All participants had normal or corrected to normal vision, and were paid $4.50/hour plus a bonus based on the quality of their performance.

### *Apparatus*

Experiment 2 used the same apparatus as in Experiment 1.

### *Design and Procedure*

***Tasks***. Participants performed two tasks in this experiment. Task 1 was an auditory-manual task. On each trial of it, participants heard either an 800 Hz or 1200 Hz tone and responded by pressing either the left index-finger or left middle-finger key, respectively. Task 2 was a visual-manual task. On each trial of it, one of eight digits (2 through 9) appeared in the center of the display monitor. If a *2*, *5*, *6*, or *9* appeared, participants pressed the right index-finger key. If a *3*, *4*, *7*, or *8* appeared, participants pressed the right middle-finger key. Task 2 had two (easy and hard) levels of response-selection difficulty. The easy version of Task 2 involved two S-R pairs that used the digits *2* and *3*, whereas the hard version involved eight S-R pairs that used the digits *2* through *9*. The stimuli for the two tasks were separated by one of five SOAs: 50, 150, 250, 500, or 1000 ms.

***Sessions***. The experiment included three sessions. Session 1 had 13 trial blocks: 3 single-task blocks, one for Task 1 and one for each level of Task 2 difficulty, and 10 dual-task blocks. These blocks were considered to be practice and not included in subsequent data analyses. Sessions 2 and 3 each contained 13 trial blocks, all of which were dual-task blocks. The first block of each session involved the hard Task 2. On all trials during these two blocks, the two task stimuli were separated by the 500-ms SOA. These two blocks were considered to be practice and not included in subsequent data analyses. Each of the other 12 blocks of Sessions 2 and 3 used all five SOAs. Here the easy and hard versions of Task 2 occurred in successive groups of three blocks each. For all participants, the first group of blocks with the easy Task 2 preceded the first group of blocks with the hard Task 2, and then the groups repeated.

***Trial blocks***. All possible tone-digit-SOA combinations occurred equally often within each trial block. Each single-task block had 24 trials. After single-task practice in Session 1, participants received three dual-task blocks involving the easy Task 2. The first and second blocks of Session 1 had 20 trials each; during them the two task stimuli were separated by the 1000-ms and 150-ms SOAs, respectively. The third block of Session 1 had 40 trials; during them the two task stimuli were separated by the 500-ms SOA. The remaining dual-task blocks of Session 1 and all dual-task blocks of Sessions 2 and 3 had 80 trials each and used all five SOAs. Participants were told at the beginning of each trial block which task(s) would be involved.

***Trials***. Each trial of each block began with a 100 Hz warning tone for 100 ms accompanied by a fixation cross in the center of the display monitor. On dual-task trials, 500 ms after the offset of the warning tone, a Task 1 tone sounded for 40 ms, and after the SOA, a Task 2 digit replaced the fixation cross. On single-task trials, only one task stimulus was presented. The serial order of task-stimulus types and SOAs were randomized within each trial block.

***Feedback***. On each trial, participants received points for correct responses and lost points for incorrect responses. Their bonus depended on their accumulated points. We awarded 200 points per trial, minus 2 points for every 10 ms taken to respond to a Task 1 stimulus, and 100 points per trial, minus 1 point for every 10 ms taken to respond to a Task 2 stimulus. We charged 200 points for every incorrect Task 1 response, and 100 points for every incorrect Task 2 response. On dual-task blocks, participants had to respond to the tone first or else both responses

were considered incorrect.[5] . Participants earned a dollar for every 20,000 points they scored and were fully informed about the reward system before the experiment began.

After each trial block, participants received more detailed feedback about their number of correct responses, mean RTs, and points. Also, for the first five blocks of Session 1 and the first block of Sessions 2 and 3, participants received feedback about response accuracy and points after each trial. Thereafter, participants received this feedback only after trials for which there were incorrect responses.

### *Results*

The data from Experiment 2 were purged of outliers and analyzed in the same way as those from Experiment 1, with Session included as an additional factor. The outlier-rejection procedure removed 4.7% of the original data set, leaving 22,121 response pairs. Figure 6 shows the mean RTs for each task in Sessions 2 and 3 as a function of Task 2 response-selection difficulty and SOA. Table 2 shows the corresponding error rates. In what follows, we discuss the results more fully for each task.

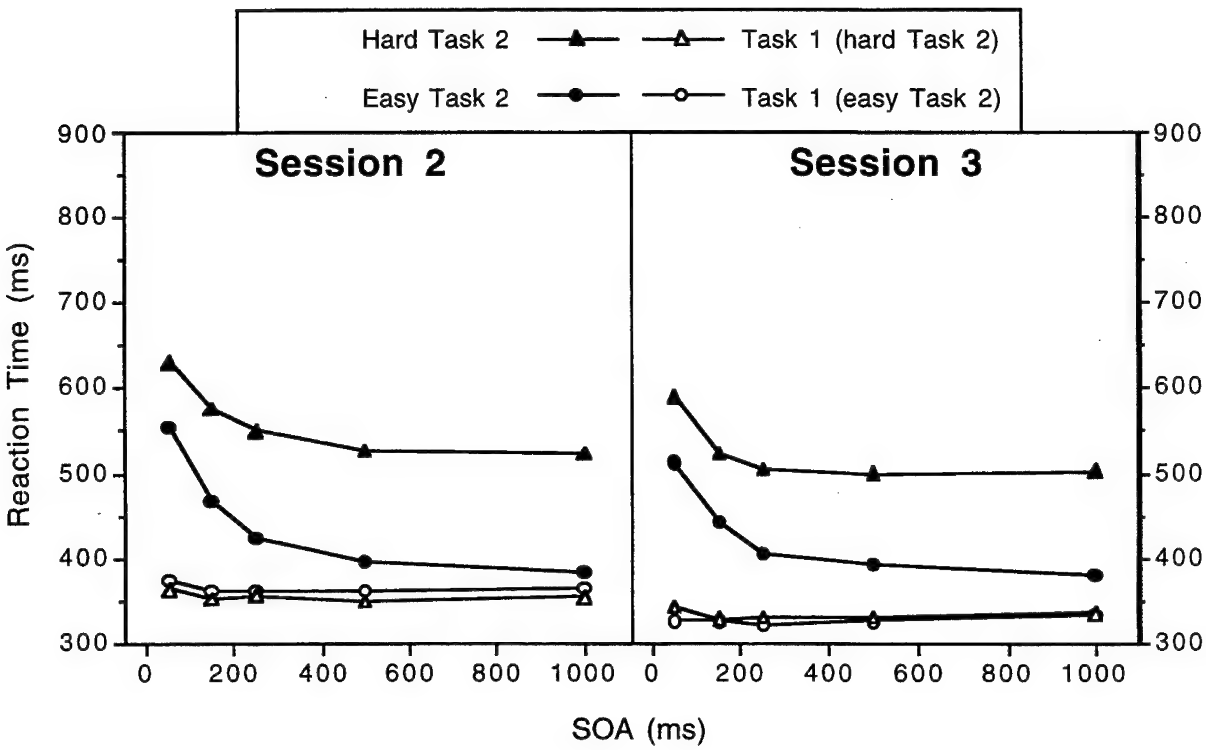


*Figure 6*. Mean RTs for Tasks 1 and 2 as a function of Task 2 response-selection difficulty and SOA in Sessions 2 and 3 of Experiment 2.

[5] Out-of-order errors occurred on less than 0.09% of trials overall.

**Table 2**

***Mean Percent Errors in Sessions 2 and 3 of Experiment 2 for Each Task as a Function of Task 2 Response-Selection Difficulty and SOA***

| | SOA (ms) | | | | |
|---|---|---|---|---|---|
| Task 2 Type | 50 | 150 | 250 | 500 | 1000 |
| | Task 1 Error Rates | | | | |
| Session 2 | | | | | |
| Hard | 2.50 | 1.88 | 1.56 | 1.35 | 1.35 |
| Easy | 3.44 | 2.60 | 1.67 | 2.40 | 1.25 |
| Session 3 | | | | | |
| Hard | 1.67 | 1.46 | 1.98 | 1.67 | 1.98 |
| Easy | 2.50 | 2.29 | 2.50 | 0.94 | 2.50 |
| | Task 2 Error Rates | | | | |
| Session 2 | | | | | |
| Hard | 6.56 | 4.79 | 6.04 | 3.96 | 4.90 |
| Easy | 3.96 | 4.17 | 3.44 | 2.08 | 2.40 |
| Session 3 | | | | | |
| Hard | 6.46 | 5.94 | 5.00 | 3.65 | 5.00 |
| Easy | 3.02 | 2.92 | 3.33 | 1.56 | 1.35 |

### *Task 1*

***Reaction times***. The main effect of Session on mean Task 1 RTs was reliable, $F(1,9) = 19.82$, $p < .005$. Across sessions, mean Task 1 RTs decreased from 360 to 330 ms. In contrast, neither the main effect of Task 2 response-selection difficulty [$F(1,9) = 0.02$, $p > .85$] nor of SOA [$F(4,36) = 2.00$, $p > .11$] on Task 1 RTs was reliable. However, there was a small but reliable interaction between the effects of Session and Task 2 difficulty, $F(1,9) = 5.55$, $p < .05$. Mean RTs for Task 1 when paired with the easy Task 2 were 9 ms slower in Session 2 and 7 ms faster in Session 3 than when Task 1 was paired with the hard Task 2. There were no other reliable effects, $p > .40$ in all cases.

***Error rates***. The overall Task 1 error rate was fairly low (1.97%). The only reliable contrast was an interaction between the effects of Session and SOA on Task 1 errors, $F(4,36) = 3.60$, $p < .05$. Error rates increased as SOA decreased in Session 2 but did not change reliably with SOA in Session 3.

### *Task 2*

***Reaction times.*** All main effects and interactions for mean Task 2 RTs were reliable. Across sessions, mean Task 2 RTs decreased from 503 to 475 ms, $F(1,9) = 15.22$, $p < .005$. Mean RTs were faster when Task 2 was easy (436 ms) than when Task 2 was hard (543 ms), $F(1,9) = 148.09$, $p < .0005$. The effect of Task 2 response-selection difficulty decreased from 116 ms in Session 2 to 97 ms in Session 3, $F(1,9) = 9.26$, $p < .05$. There was also a moderate SOA effect, $F(4,36) = 94.59$, $p < .0005$ ( Figure 6). The SOA effect decreased from Session 2 to 3, $F(4,36) = 8.26$, $p < .0005$. Similarly, there was a reliable interaction between the effects of Task 2 response-selection difficulty and SOA on Task 2 RTs, $F(4,36) = 17.35$, $p < .0005$; the difficulty effect decreased as SOA decreased. Finally, the triple interaction between the effects of Session, Task 2 difficulty, and SOA on mean Task 2 RTs was reliable, $F(4,36) = 2.97$, $p < .05$.

Figure 7 shows the response-selection difficulty effects on mean Task 2 RTs at the shortest and longest SOAs for Sessions 2 and 3. The differences between the difficulty effects at these SOAs (64 ms in Session 2 and 44 ms in Session 3) were reliable during each session, $t(9) = 5.69$, $p < .0005$ for Session 2, and $t(9) = 5.97$, $p < .0005$ for Session 3.

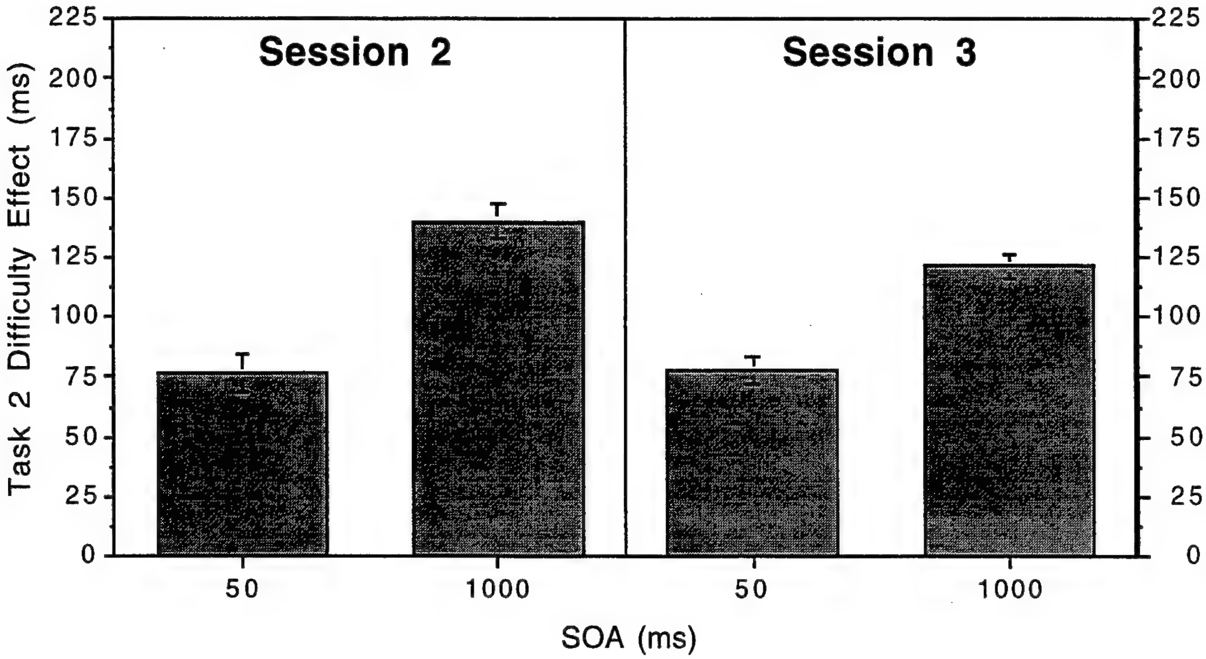


*Figure 7.* Response-selection difficulty effects and standard-error bars for mean Task 2 RTs at the shortest and longest SOAs in Sessions 2 and 3 of Experiment 2. Standard-error bars were derived from the mean squared error of the F-test for determining the reliability of the difference between the heights of the bars.

***Error rates*.** The overall Task 2 error rate was 4.03%. There was a reliable main effect of Task 2 response-selection difficulty on Task 2 errors, $F(1,9) = 17.16, p < .005$. Participants made more errors when Task 2 was hard (5.23%) than when Task 2 was easy (2.82%). The effect of SOA was also reliable, $F(4,36) = 7.86, p < .0005$; error rates increased as SOA decreased. No other effects on Task 2 error rates were reliable.

### *Discussion*

The underadditive interaction between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs replicates both Experiment 1 and prior findings by Hawkins et al. (1979). The difficulty effect was 64 ms less at the shortest SOA than at the longest SOA in Session 2, and 44 ms less in Session 3 (Figure 7). These data cannot easily be explained by the traditional RSB hypothesis. Instead, they strongly suggest that response selection for Tasks 1 and 2 temporally overlapped in Experiment 2. This outcome supports the AEC models of Meyer and Kieras (1997a, 1997b, 1997c; Meyer et al., 1995), suggesting that when participants have a response-selection bottleneck, it is optional and strategic rather than structural and immutable.

Furthermore, the similarity of the underadditive interactions between the effects of Task 2 response-selection difficulty and SOA on Task 2 RTs in Experiment 2 (64/44 ms), Experiment 1 (79 ms), and Karlin and Kestenbaum (1968) (54 ms) suggests that all of them stemmed from overlapping response-selection processes rather than from the effects of stimulus-encoding difficulty. Even the decrease in the magnitude of this interaction from Session 2 to 3 of Experiment 2 cannot be attributed to a decrease in the amount of response-selection overlap between Tasks 1 and 2. Instead, the smaller interaction in Session 3 stemmed largely from the smaller Task 2 response-selection difficulty effect there. Specifically, as shown in Figure 7, the only change from Session 2 to 3 occurred for the Task 2 difficulty effect (it decreased by about 20 ms) at the 1000-ms SOA.

Of course, some ardent advocates of immutable structural response-selection bottlenecks still might argue that the results of Experiment 2 stem from effects of S-R numerosity on the duration of stimulus encoding for Task 2 (Pashler, 1984; 1994a; Pashler & Baylis, 1991). If so, then the traditional RSB hypothesis could perhaps be maintained. However, this argument loses much of its force upon careful inspection of results from the many previous studies that have used symbolic stimuli and manipulated S-R numerosity to influence response-selection difficulty.

For example, consider a study by Sternberg (1969, Experiment 5). He orthogonally manipulated S-R numerosity, S-R compatibility, and visual stimulus discriminability (intact vs. degraded) in a digit-naming task. His participants produced an interaction of about 90 ms between the effects of S-R numerosity and S-R compatibility on mean RTs, which was almost 25% of the overall RT magnitude. Because Sternberg's S-R compatibility effect presumably occurred during response selection (Kornblum, Hasbroucq, & Osman, 1990; McCann & Johnston, 1992; Sanders, 1980; Sternberg, 1969), this large interaction implies that much of the S-R numerosity effect likewise took place there. In contrast, Sternberg's participants produced only about a 10-ms interaction between the effects of S-R numerosity and visual-stimulus discriminability on mean RTs, which was just 3% of the overall RT magnitude. Because the stimulus-discriminability effect presumably occurred during stimulus encoding (Sanders, 1980; Sternberg, 1969), this very small interaction implies that little, if any, of Sternberg's S-R numerosity effect took place there. As Sternberg himself concluded, "One might... argue from the relative weakness of the interaction [between S-R numerosity and stimulus discriminability] to the relative weakness of the effect of [S-R numerosity] on the [encoding] stage" (p. 301). Also supporting this conclusion, other researchers have found virtually no effects of S-R numerosity on the duration of stimulus encoding (Brainard et al., 1962; Davis, Moray, & Treisman, 1961; Gottsdanker, 1969; Morin & Forrin, 1965; Theios, 1973).

Furthermore, even Sternberg's (1969, Experiment 5) reliable 10-ms interaction between the effects of S-R numerosity and stimulus discriminability may have been an artifact of his experimental design. The design condition with the two S-R pairs required participants to discriminate between the digits *1* and *8*, which have distinctive perceptual features (lines vs. curves) that could facilitate stimulus encoding in this condition. These features were less distinctive in the condition with eight S-R pairs; as a result, they could have caused the manipulation of S-R numerosity to affect stimulus encoding indirectly. Better control of perceptual feature distinctiveness across the levels of S-R numerosity presumably would have yielded a null interaction between S-R numerosity and discriminability factors in Sternberg's study, just as other investigators have found.

Given these preceding considerations, two strong inferences follow from results of Experiment 2: (a) our manipulation of S-R numerosity in the secondary task had virtually all of its effect on the duration of response selection for Task 2; and (b) the large interaction of this effect with that of SOA on Task 2 RTs indicates that at short SOAs, responses for Tasks 1 and 2 were selected concurrently. Further supporting such inferences, our third experiment involves manipulating another complementary factor, S-R compatibility, whose effects presumably occur during response selection rather than stimulus encoding or movement production. Again we show that, as in Experiments 1 and 2, the manipulation of such a factor in Task 2 yields underadditive effects with those of SOA on mean Task 2 RTs, reinforcing our previous inferences about the mutability of response-selection bottlenecks and the viability of AEC models.

## Experiment 3

In Experiment 3, Task 1 was a two-choice auditory-manual task similar to that of Experiment 2, and Task 2 was a spatial visual-manual task. Task 2 response-selection difficulty was manipulated by varying the compatibility of the S-R pairs therein. For this manipulation, the mappings from stimulus location to finger response were either spatially ordered or mixed. Many prior studies have varied S-R compatibility in this way as a paradigmatic manipulation of response-selection difficulty (Duncan, 1977; Fagot & Pashler, 1992; Fitts & Seeger, 1953; Kornblum et al., 1990; McCann & Johnston, 1992).

If the traditional RSB hypothesis were correct, and if the underadditive interactions found in Experiments 1 and 2 were caused by effects of S-R numerosity on stimulus encoding, then the S-R compatibility effect on mean Task 2 RTs in Experiment 3 should be additive with the effect of SOA. If, however, response selection for Tasks 1 and 2 can overlap, then contrary to the RSB hypothesis but consistent with AEC models, an underadditive interaction between the effects of S-R compatibility and SOA on Task 2 RTs should emerge again.

## Method

### Participants

Eight right-handed undergraduate students (4 males and 4 females) from the University of Michigan participated in this study as paid volunteers. They came from the same population as those in the previous experiments but had not been tested previously. Participants had normal or corrected to normal vision, and were paid $5.00/hour plus a bonus based on the quality of their performance.

### Apparatus

Experiment 3 used the same apparatus as in the previous experiments.

### Design and Procedure

***Tasks***. Participants performed two tasks in this experiment. Task 1 was an auditory-manual task. On each trial of it, participants heard either an 1120 Hz or 1450 Hz tone and responded by pressing the left middle-finger or left index-finger key, respectively. Task 2 was a visual-manual task. On each trial of it, an *O* replaced one of four dashes in a horizontal row in the center of the display monitor. Task 2 had two (easy and hard) levels of response-selection difficulty. In the easy version of Task 2, participants pressed the right index, middle, ring, or little finger key if the *O* appeared in far left, middle left, middle right, or far right spatial position, respectively. In the hard version of Task 2, participants pressed the right index, middle, ring, or little finger key if the *O* appeared in the middle left, far right, far left, or middle right position, respectively. The stimuli for the two tasks were separated by one of five SOAs: 50, 150, 250, 500, or 1000 ms.

***Sessions***. The experiment included three sessions. Session 1 had 22 trial blocks: 14 single-task blocks, and 8 dual-task blocks. These blocks were considered to be practice and not included in subsequent data analyses. Sessions 2 and 3 each consisted of 24 trial blocks: 8 single-task blocks and 16 dual-task blocks. The single-task blocks were considered to be practice and not included in subsequent data analyses. The dual-task blocks were paired such that for each block pair, either the easy or hard Task 2 had to be performed, and the difficulty of Task 2 alternated across block pairs. Preceding each alternating block pair was a single-task block involving the version of Task 2 to be performed next. The serial order of the easy and hard secondary tasks was counterbalanced across participants.

***Trial blocks***. All possible tone-location-SOA combinations occurred equally often within each trial block. Single-task blocks had 20 trials each, and dual-task blocks had 40 trials each. Participants were told at the beginning of each block which task(s) would be involved.

***Trials***. Each trial of each block began with an 880 Hz warning tone for 50 ms and a row of four dashes presented in the center of the display monitor. On dual-task trials, 500 ms after the offset of the warning tone, a Task 1 tone sounded for 40 ms, and after the SOA, a Task 2 stimulus replaced one of the dashes. On single-task trials, only one task stimulus was presented. The serial order of task-stimulus types and SOAs were randomized within each trial block.

***Feedback***. The reward system was identical to the one in Experiment 1 except that participants earned a dollar for every 40,000 points they scored. After each trial block, participants received detailed feedback about their number of correct responses, mean RTs, and points.[6] For the first 10 blocks of Session 1, participants received feedback about response accuracy and points

[6] Out-of-order errors occurred on less than 0.06% of trials overall.

after each trial. Subsequently, participants received this feedback only after trials for which there were incorrect responses.

### *Results*

The data from Experiment 3 were purged of outliers and analyzed in the same way as those from Experiment 2. The outlier-rejection procedure removed 5.2% of the original data set, leaving 9,284 response pairs. Figure 8 shows the mean RTs for each task in Sessions 2 and 3 as a function of Task 2 response-selection difficulty and SOA. Table 3 shows the corresponding error rates. In what follows, we discuss the results more fully for each task.

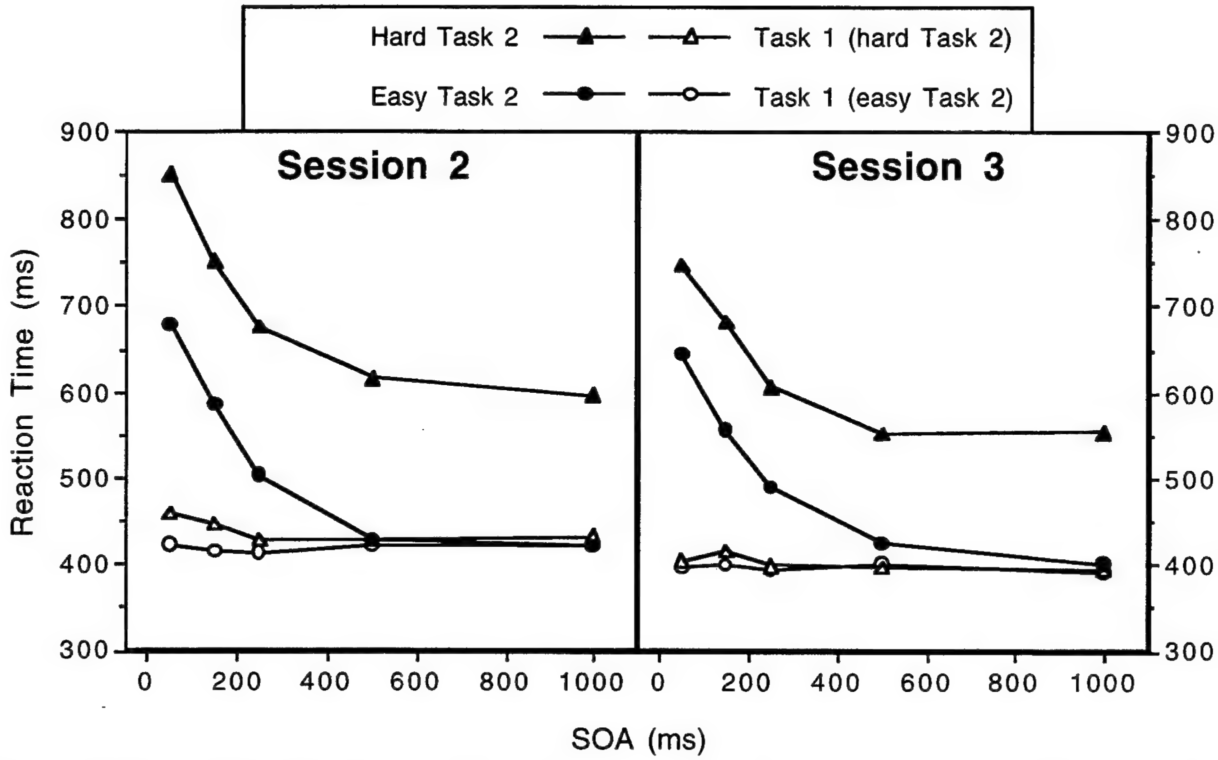


*Figure 8*. Mean RTs for Tasks 1 and 2 as a function of Task 2 response-selection difficulty and SOA in Sessions 2 and 3 of Experiment 3.

### *Task 1*

***Reaction times***. The main effect of Session on Task 1 RTs was reliable, $F(1,7) = 12.24, p < .05$. Across sessions, mean Task 1 RTs decreased from 430 to 401 ms. Neither the main effect of Task 2 response-selection difficulty [$F(1,7) = 1.95, p > .20$] nor SOA on Task 1 RTs was reliable, $F(4,28) = 2.02, p > .10$. There was a reliable interaction between the effects of Session and Task 2 difficulty, $F(1,7) = 5.39, p < .05$. The Task 2 difficulty effect on mean Task 1 RTs decreased from 20 ms in Session 2 to 5 ms in Session 3. There was also a small but reliable interaction between the effects of Task 2 difficulty and SOA, $F(4,28) = 2.83, p < .05$. The effect of Task 2 difficulty on mean Task 1 RTs increased as SOA decreased. There were no other reliable interactions.

***Error rates***. The overall Task 1 error rate was fairly low (1.66%). The only reliable interaction was between the effects of Session and Task 2 response-selection difficulty, $F(1,7) = 7.09, p < .05$. Participants made more Task 1 errors in Session 2 and less in Session 3 when performing the hard Task 2 than when performing the easy Task 2, but the error rates were less than 3% in all cases.

**Table 3**

***Mean Percent Errors in Sessions 2 and 3 of Experiment 3 for Each Task as a Function of Task 2 Response-Selection Difficulty and SOA***

| Task 2 Type | SOA (ms) 50 | 150 | 250 | 500 | 1000 |
|---|---|---|---|---|---|
| | Task 1 Error Rates | | | | |
| Session 2 | | | | | |
| Hard | 3.13 | 1.37 | 1.37 | 1.95 | 2.15 |
| Easy | 2.54 | 1.56 | 1.37 | 0.98 | 0.78 |
| Session 3 | | | | | |
| Hard | 1.37 | 1.56 | 0.98 | 1.17 | 1.76 |
| Easy | 0.98 | 2.34 | 2.15 | 1.56 | 2.15 |
| | Task 2 Error Rates | | | | |
| Session 2 | | | | | |
| Hard | 5.27 | 2.15 | 1.37 | 4.30 | 2.34 |
| Easy | 2.93 | 1.37 | 1.17 | 1.17 | 2.34 |
| Session 3 | | | | | |
| Hard | 2.73 | 3.13 | 2.34 | 2.54 | 4.88 |
| Easy | 2.54 | 1.95 | 2.15 | 1.76 | 2.34 |

***Task 2***

***Reaction times***. All main effects on mean Task 2 RTs were reliable. Across sessions, mean Task 2 RTs decreased from 612 to 567 ms, $F(1,7) = 7.29$, $p < .05$; mean Task 2 RTs were faster when Task 2 was easy (514 ms) than when Task 2 was hard (664 ms), $F(1,7) = 56.72$, $p < .0005$; and there was a large SOA effect, $F(4,28) = 43.05$, $p < .0005$ (Figure 8). The interaction between the effects of Session and Task 2 response-selection difficulty on mean Task 2 RTs was reliable, $F(1,7) = 16.26$, $p < .01$. Across sessions, the Task 2 difficulty effect decreased from 175 ms to 125 ms. The interaction between the effects of Task 2 difficulty and SOA on mean Task 2 RTs was not reliable, $F(4,28) = 2.02$, $p > .10$, but there was a reliable triple interaction between the effects of Session, Task 2 difficulty, and SOA, $F(4,28) = 2.74$, $p < .05$.

The mean Task 2 RTs were also analyzed separately for each session. All main effects on them were reliable for each session, $p < .0005$ in all cases. The interaction between the effects of Task 2 response-selection difficulty and SOA was not reliable for Session 2, $F(4,28) = 0.62$, $p > .65$, but was reliable for Session 3, $F(4,28) = 4.42$, $p < .01$. Figure 9 shows the response-selection difficulty effects on mean Task 2 RTs at the shortest and longest SOAs for Sessions 2 and 3. The 51-ms difference between the difficulty effects at these SOAs in Session 3 was reliable, $t(7) = 3.72$, $p < .01$.

***Error rates***. The overall Task 2 error rate was 2.54%. Only SOA affected it reliably, $F(4,28) = 3.10$, $p < .05$. Participants made more errors at the 50-ms SOA than at any other SOA.

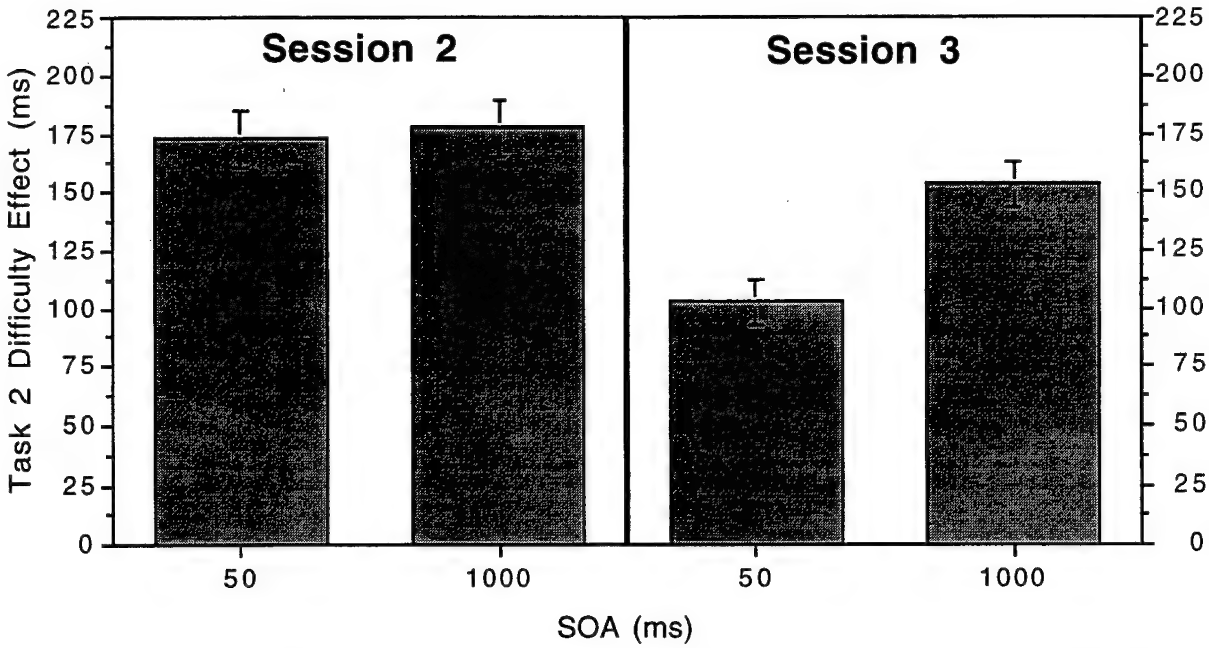


*Figure 9*. Response-selection difficulty effects and standard-error bars for mean Task 2 RTs at the shortest and longest SOAs in Sessions 2 and 3 of Experiment 3. Standard-error bars were derived from the mean squared error of the F-test for determining the reliability of the difference between the heights of the bars.

### *Discussion*

The underadditive interaction between the effects Task 2 response-selection difficulty and SOA on mean Task 2 RTs in Session 3 of Experiment 3 casts further doubt on the existence of an immutable structural response-selection bottleneck. The difficulty effect was 51 ms less at the shortest SOA than at the longest SOA (Figure 9). Because manipulations of S-R compatibility are widely accepted to affect response selection (Fagot & Pashler, 1992; Fitts & Seeger, 1953; Kornblum et al., 1990; McCann & Johnston, 1992; Sanders, 1980; Sternberg, 1969), the interaction of their effects with SOA is neither predicted nor easily explained by the RSB hypothesis. Instead, consistent with AEC models (Meyer & Kieras, 1997a, 1997b, 1997c; Meyer et al., 1995), it appears that response-selection processes can occur concurrently for Tasks 1 and 2 in the PRP procedure. Additionally, the similarity of these underadditive interactions in Experiment 1 (79 ms), Experiment 2 (64/44 ms), and Experiment 3 (51 ms) has clear implications: all three interactions presumably stemmed from concurrent Task 1 and Task 2 response-selection processes, rather than from differences in stimulus encoding or other ancillary processing stages.

Furthermore, the additive effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs during Session 2 suggest that, consistent with AEC models (Meyer & Kieras, 1997a, 1997b, 1997c; Meyer et al., 1995), people may flexibly modify their task-scheduling strategies. If people have adaptive executive control over task scheduling (i.e., when to suspend and resume Task 2 processing), then it is to be expected that these strategies might change with practice. During Session 2, when participants are relatively unfamiliar with the tasks and not yet confident about their ability to perform them concurrently, they may be more inclined to adopt a cautious scheduling strategy that locks out Task 2 response selection until Task 1 response selection has been completed. One reason for adopting such a cautious scheduling strategy is that it helps minimize the chances of making Task 2 responses before Task 1 responses. However, during Session 3, after receiving more practice, participants may be more inclined to adopt a daring scheduling strategy, which entails moving their Task 2 lockout point from before to after response selection for Task 2, thereby allowing response-selection processes for Tasks 1 and 2 to overlap.

Such daring task scheduling would be optimal (if performed without adversely affecting error rates) because it helps minimize Task 2 RTs (especially for the hard version of Task 2) at the short SOAs.

The underadditive interaction between the effects of Task 2 response-selection difficulty and SOA on Task 2 RTs emerged in Session 3 even though the Task 2 difficulty effect on Task 2 RTs was smaller in Session 3 than in Session 2. Notice in Figure 9 that the Task 2 difficulty effect decreases from Session 2 to 3 at both the 50-ms and 1000-ms SOA, but that the decrease is most pronounced at the shortest SOA. This increasing interaction in the context of a decreasing Task 2 difficulty effect strongly suggests that participants changed their task scheduling from a cautious strategy (Task 2 response-selection postponement) in Session 2 to a daring strategy (Task 2 response-selection overlap) in Session 3.[7] Similarly, Meyer and Kieras (1996, 1997b, 1997c) have presented additional evidence that expert performers in other multiple-task situations (e.g., aircraft cockpit operation) use daring task-scheduling strategies as well.

### *Multiple Structural Bottlenecks?*

Comparing task performance for Sessions 2 and 3 of Experiment 3 also lets us test a hypothesis proposed by De Jong (1993). He proposed two immutable structural bottlenecks: one for response selection, and another for movement production. This proposal was offered to explain underadditive interactions between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs (e.g., Karlin & Kestenbaum, 1968). According to De Jong, such interactions may occur, even though there is a response-selection bottleneck, when both tasks in a dual-task situation involve the same response modality. The involvement of the same (e.g., manual) response modality for both tasks could cause movement production in Task 1 to impose a motor refractory period (MRP) on Task 2. Under these conditions, the Task 1 MRP would be the minimum time (estimated as about 200 ms) required between the beginning of movement production for Task 1 and the beginning of movement production for Task 2. If the duration of response selection for the easy version of Task 2 is less than the motor refractory period for Task 1, then slack would occur in Task 2 processing immediately before the Task 2 movement-production stage. Given that Karlin and Kestenbaum's mean Task 2 RT for the simple-RT task at the longest SOA was less than 200 ms, the slack caused by the movement-production bottleneck in Task 2 processing could have led to their underadditive interaction for mean Task 2 RTs.

De Jong's multiple structural-bottleneck hypothesis perhaps could account likewise for the results from our Experiments 1 and 2. The response-selection stages for the easy secondary tasks in these two experiments may have taken less than 200 ms each. However, the results from Experiment 3 cannot be explained in this way.

During Experiment 3, the interaction between the effects of S-R compatibility and SOA on mean Task 2 RTs became underadditive with practice (Figures 7 and 8) even though the mean RT for the easy Task 2 at the longest SOA stayed virtually the same across sessions (it decreased by less than 20 ms). This suggests that the nature and duration of Task 2 response selection did not change much, if at all, from Session 2 to Session 3. Therefore, according to De Jong's (1993) hypothesis, one of two cases should have held: (a) the duration of the response-selection stage for the easy Task 2 was less than the MRP, and S-R compatibility should have produced an underadditive interaction with SOA in both sessions; or (b) the duration of the response-selection stage for the easy Task 2 was greater than the MRP, and S-R compatibility should have produced additive effects with SOA in both sessions. Given that neither of these two cases (i.e., consistent additivity or consistent interaction) actually occurred, a simple version of the multiple structural-bottleneck hypothesis may be rejected for Experiment 3. Instead, our results continue to suggest the existence of flexible task-scheduling strategies, as the AEC models of Meyer and Kieras (1997a, 1997b; Meyer et al., 1995) would predict.

[7] Consistent with this suggestion are results from Experiment 2 (Figure 7), where both the Task 2 response-selection difficulty effect on Task 2 RTs and its interaction with the effects of SOA decreased across sessions, and where no change in participants' task-scheduling strategies is postulated.

Nevertheless, at this point, an elaborated version of the multiple structural-bottleneck hypothesis still might have some merit. Recently, following the lead of Meyer and Kieras (1992, 1994), De Jong (1995) has proposed that executive processes can control the scheduling of task performance in the PRP procedure. Within the framework of his multiple structural-bottleneck hypothesis, he proposed that Task 2 response selection may not begin automatically after Task 1 response selection ends. Rather, the onset Task 2 response selection may be initiated by "higher-order control processes." Although De Jong did not discuss this possibility explicitly, practice might affect these postulated control processes as it does under the AEC models. That is, perhaps early in practice participants delay the start of Task 2 response selection until well after Task 1 movement production is underway (analogous to a cautious lockout strategy under the AEC models). After practice, however, participants may develop the ability to start Task 2 response selection immediately after the completion of Task 1 response selection.

Thus, a version of the structural RSB hypothesis may still be tenable if it includes two additional mechanisms: (a) a second structural bottleneck in movement production; and (b) an ability to strategically alter the onset of Task 2 response selection with practice. According to this view, the results from Experiment 3 perhaps occurred in the following way. During Session 2, participants could have delayed the start of Task 2 response selection until Task 1 movement production was well underway. Consequently, the movement-production bottleneck would not have affected Task 2 RTs then because all the processing slack took place before Task 2 response selection. During Session 3, however, participants could have begun Task 2 response selection immediately after completing Task 1 response selection, so the movement-production bottleneck would have caused processing slack after the easy version of Task 2, which yields the underadditive interaction between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs.

Yet even this elaborated version of the RSB hypothesis -- with two immutable structural bottlenecks and strategic executive control processes -- is not viable. It may be rejected definitively on the basis of results from a fourth experiment, which circumvents De Jong's (1993, 1995) postulated structural movement-production bottleneck.

## Experiment 4

Experiment 4 was identical to Experiment 3 except that it combined a two-choice auditory-vocal instead of auditory-manual Task 1 with a visual-manual Task 2. According to De Jong (1993), such task combinations whose responses require different response modalities are not subject to the MRP. In fact, he used tasks with manual and pedal responses to circumvent the putative structural movement-production bottleneck (De Jong, 1993). The elaborated structural RSB hypothesis therefore predicts that under the conditions of Experiment 4, Task 2 response-selection difficulty and SOA must have additive effects on mean Task 2 RTs. That is, this additivity cannot be obscured by the presence of a secondary structural movement-production bottleneck. On the other hand, as before, the AEC models of Meyer and Kieras (1997a, 1997b, 1997c; Meyer et al., 1995) predict that Task 2 response-selection difficulty and SOA may affect mean Task 2 RTs interactively, because the response-selection processes associated with Tasks 1 and 2 again can occur concurrently.

Furthermore, we might expect that the use of different response modalities for Tasks 1 and 2 in Experiment 4 would yield more extreme results than occurred in Experiment 3. Our AEC models are based on a cognitive architecture known as Executive Process/Interactive Control, or EPIC (Meyer & Kieras, 1997a, 1997b, 1997c; Meyer et al., 1995). According to EPIC, there is no immutable structural central response-selection bottleneck, nor do EPIC's various motor processors share a common movement-production bottleneck. For example, EPIC's manual and vocal motor processors can make independent responses at the same time (cf. McLeod, 1977; McLeod & Posner, 1984). Given this architecture, a PRP experiment whose Tasks 1 and 2 require vocal and manual responses respectively might induce people to adopt a more daring scheduling strategy (i.e., one with a later Task 2 lock out point) than when the tasks involve the same response modality, which precludes multiple independent responses. If so, then this would

have the following consequences on mean Task 2 RTs: (a) the predicted underadditive interaction between the effects of Task 2 response-selection difficulty and SOA may occur in Session 2 as well as Session 3 of Experiment 4; (b) at the shortest SOAs, the Task 2 difficulty effect may be smaller in Experiment 4 than in Experiment 3; and (c) the Task 2 PRP effect may be smaller in Experiment 4 than in Experiment 3.

## *Method*

### *Participants*

Six right-handed undergraduate students (3 males and 3 females) from the University of Michigan participated in this study as paid volunteers. They came from the same population as those in the previous experiments but had not been tested previously. Participants had normal or corrected to normal vision, and were paid $5.00/hour plus a bonus based on the quality of their performance.

### *Apparatus*

Experiment 4 used the same apparatus as in the previous experiments. Participants' vocal responses triggered a MED Associates voice-activated switch (ANL-923), which signaled the computer that a vocal response had been made.

### *Design and Procedure*

All aspects of the design and procedure were identical to Experiment 3 except that Task 1 required vocal rather than manual responses. Participants responded to the 1120 Hz tone by saying "low" and to the 1450 Hz tone by saying "high."[8]

## *Results*

The data from Experiment 4 were purged of outliers and analyzed in the same way as those from Experiments 2 and 3. The outlier-rejection procedure removed 5.7% of the original data set, leaving 6,882 response pairs. Figure 10 shows the mean RTs for each task in Sessions 2 and 3 as a function of Task 2 response-selection difficulty and SOA. Table 4 shows the corresponding error rates. In what follows, we discuss the results more fully for each task.

### *Task 1*

***Reaction times***. The main effect of Session on mean Task 1 RTs was reliable, $F(1,5) = 10.59$, $p < .05$. Across sessions, mean Task 1 RTs decreased from 510 to 493 ms. There was also a small but reliable main effect of SOA on Task 1 RTs, $F(4,20)=3.51$, $p<.05$. Across sessions and Task 2 difficulty, Task 1 RTs increased as SOA decreased. Neither the main effect of Task 2 response-selection difficulty [$F(1,5) = 1.85$, $p > .20$] nor any interaction was reliable.

***Error rates***. The overall Task 1 error rate was 2.92%. The main effect of SOA was reliable, $F(4,20)=10.42$, $p<.0005$. Participants made more errors on Task 1 when the SOA was short (4.69%) than when the SOA was long (2.34%). The interaction between the effects of Session and SOA was also reliable, $F(4,20)=3.86$, $p<.05$. SOA affected Task 1 error rates more on Session 2 than on Session 3. No other main effects or interactions were reliable.

[8] Out-of-order errors occurred on less than 1.00% of trials overall.

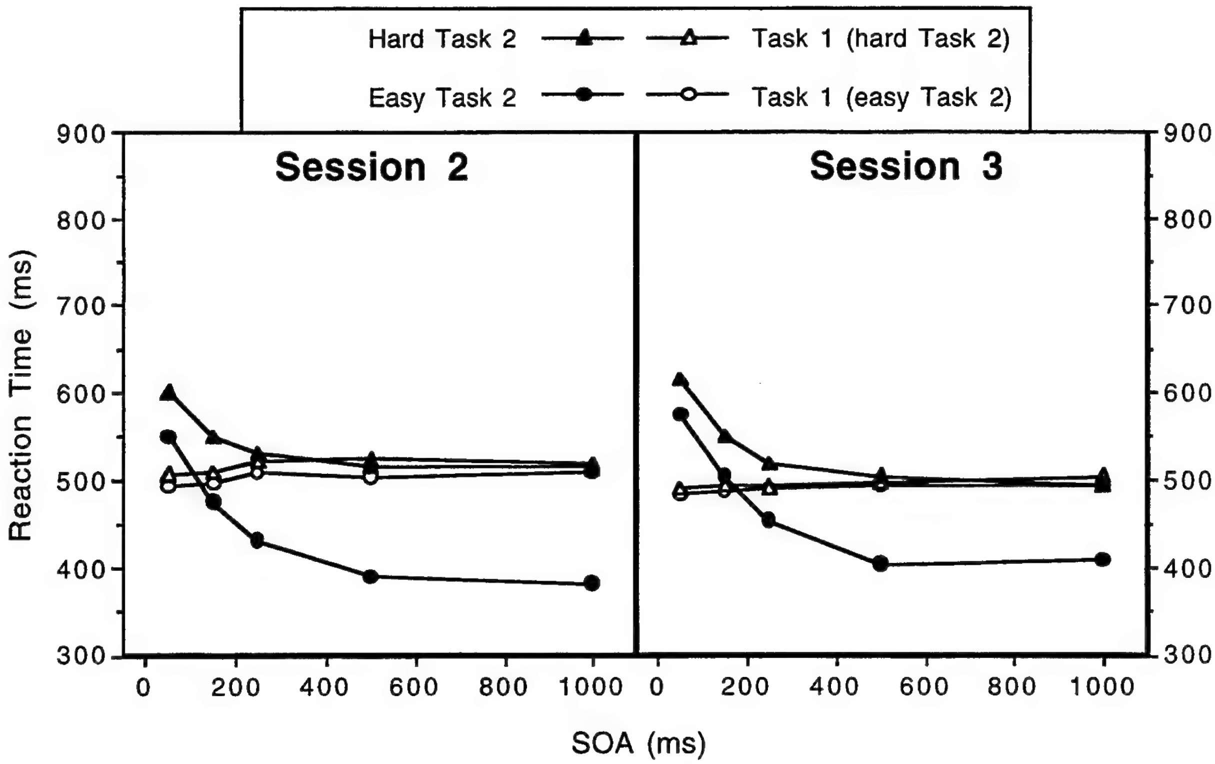


*Figure 10.* Mean RTs for Tasks 1 and 2 as a function of Task 2 response-selection difficulty and SOA in Sessions 2 and 3 of Experiment 4.

**Table 4**

***Mean Percent Errors in Sessions 2 and 3 of Experiment 4 for Each Task as a Function of Task 2 Response-Selection Difficulty and SOA***

| | SOA (ms) | | | | |
|---|---|---|---|---|---|
| Task 2 Type | 50 | 150 | 250 | 500 | 1000 |
| | Task 1 Error Rates | | | | |
| Session 2 | | | | | |
| Hard | 2.86 | 1.30 | 2.86 | 2.35 | 1.30 |
| Easy | 7.82 | 2.87 | 1.57 | 2.08 | 1.56 |
| Session 3 | | | | | |
| Hard | 3.13 | 1.30 | 3.39 | 1.82 | 3.65 |
| Easy | 4.95 | 4.95 | 2.87 | 2.87 | 2.87 |
| | Task 2 Error Rates | | | | |
| Session 2 | | | | | |
| Hard | 1.30 | 0.78 | 2.08 | 1.56 | 2.60 |
| Easy | 0.52 | 1.56 | 1.82 | 1.83 | 3.39 |
| Session 3 | | | | | |
| Hard | 0.52 | 1.82 | 1.82 | 4.17 | 3.12 |
| Easy | 1.04 | 1.56 | 3.65 | 2.87 | 3.39 |

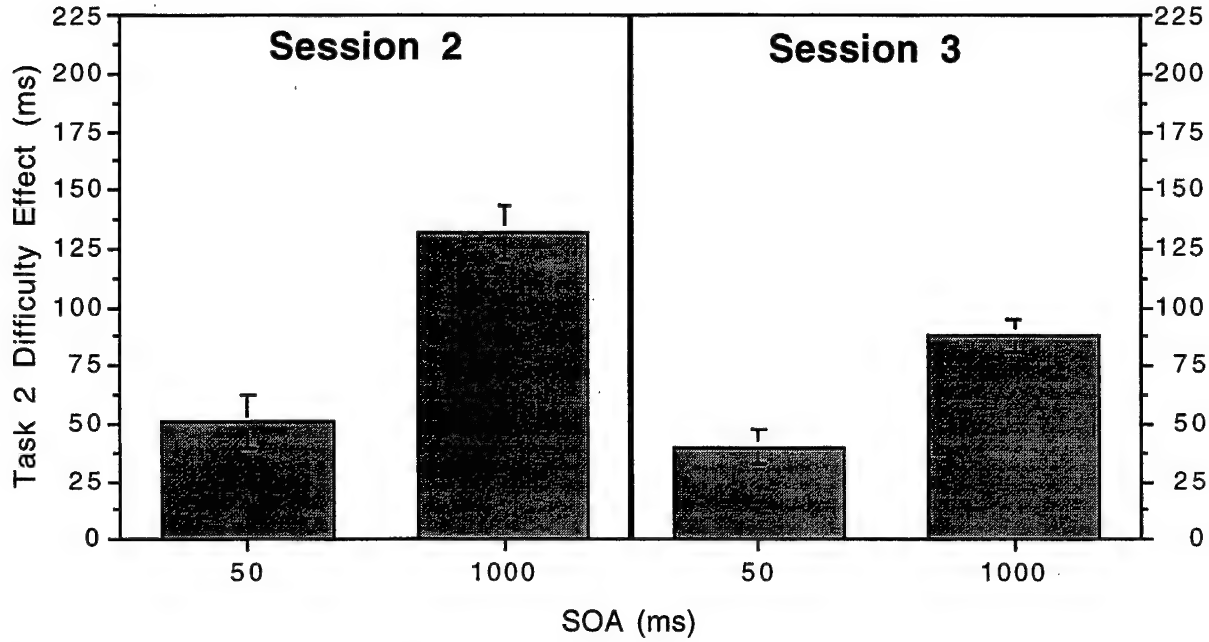


*Figure 11*. Response-selection difficulty effects and standard-error bars for mean Task 2 RTs at the shortest and longest SOAs in Sessions 2 and 3 of Experiment 4. Standard-error bars were derived from the mean squared error of the F-test for determining the reliability of the difference between the heights of the bars.

### *Task 2*

***Reaction times***. The main effects of Task 2 response-selection difficulty [$F(1,5)=52.63$, $p<.001$], SOA [$F(1,5)=15.79$, $p<.0005$], and the interaction between these effects [$F(4,20)=12.26$, $p<.0005$] on mean Task 2 RTs were reliable. Across sessions, mean Task 2 RTs were faster when Task 2 was easy (458 ms) than when Task 2 was hard (540 ms), and there was a moderate SOA effect (Figure 10). Session did not affect Task 2 RTs reliably, $F(1,5)=0.42$, nor did any other interaction.

Figure 11 shows the response-selection difficulty effects on mean Task 2 RTs at the shortest and longest SOAs for Sessions 2 and 3. The difference between the difficulty effects at these SOAs (81 ms in Session 2 and 48 ms in Session 3) was reliable during each session, $t(5)=4.99$, $p<.005$ for Session 2, and $t(5)=4.77$, $p<.01$ for Session 3.

***Error rates***. The overall Task 2 error rate was 2.07%. No main effects or interactions were reliable.

***Comparisons between Experiments 3 and 4***. The mean Task 2 RTs for Experiments 3 and 4 were combined and analyzed through an ANOVA that included Experiment as a factor along with Session, Task 2 response-selection difficulty, and SOA. Several resulting effects were reliable as predicted by the AEC models. For example, there was a reliable four-way interaction between the effects of Experiment, Session, Task 2 response-selection difficulty, and SOA, $F(4,48)=3.44$, $p<.01$. This suggests that in Experiment 4, the two-way interaction between the effects of Task 2 difficulty and SOA on mean Task 2 RTs occurred during both sessions, whereas in Experiment 3, it only occurred during Session 3. Additionally, there was a reliable interaction between the effects of Experiment and SOA, $F(4,48)=4.42$, $p<.005$. The overall SOA effect on mean Task 2 RTs was smaller in Experiment 4 than in Experiment 3.

### *Discussion*

The effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs interacted during both sessions of Experiment 4, casting additional grave doubts on the existence of an immutable structural response-selection bottleneck.[9] Contrary to the predictions of an elaborated RSB hypothesis with a secondary movement-production bottleneck and strategic executive control processes (De Jong, 1993, 1995), but consistent with the predictions of AEC models (Meyer & Kieras, 1997a, 1997b; Meyer et. al., 1995), an underadditive interaction was again obtained. Furthermore, such underadditivity occurred even though Tasks 1 and 2 involved different response modalities, precluding ancillary contributions from a secondary structural movement-production bottleneck.

Additionally, the differences between the Task 2 RTs from Experiments 3 and 4 also support the AEC models (Meyer & Kieras, 1997a, 1997b, 1997c; Meyer et. al., 1995). The use of different response modalities for the two tasks in Experiment 4 appears to have allowed participants to adopt a more daring task-scheduling strategy than did those in Experiment 3. This change of strategy accounts for several differences between the results of the two experiments. For example, the larger and more prevalent interaction between Task 2 response-selection difficulty and SOA effects in Experiment 4, together with the smaller SOA effect in Experiment 4, are explained. Thus, Experiment 4 adds to the mounting evidence that people have flexible adaptive control over their task-scheduling strategies.

## General Discussion

The present four experiments show that response-selection bottlenecks are *not* structural or immutable. Experiments 1 and 2 replicate and extend previous PRP studies (Karlin & Kestenbaum, 1968 and Hawkins et al., 1979, respectively) in which response-selection processes for two tasks temporally overlapped when the secondary task involved a manipulation of S-R numerosity. Effects of S-R numerosity on stimulus encoding cannot account for the results of Hawkins et al. or our Experiment 2, which involved highly familiar and discriminable digit stimuli for Task 2. Experiments 3 and 4 extend these results to include an S-R compatibility factor, which provides a prototypical manipulation of response-selection difficulty. The similar magnitudes of the underadditive interactions across our experiments constitute further evidence that S-R numerosity primarily affects response-selection difficulty. Finally, Experiment 4 shows that using primary and secondary tasks with different response modalities produces *more* temporal overlap among response-selection processes, not less as predicted by De Jong (1993). Taken together, these results strongly support the AEC models of Meyer and Kieras (1997a, 1997b, 1997c; Meyer et al., 1995).

Given that response-selection processes for Tasks 1 and 2 overlapped in our experiments, one might then wonder why the response-selection difficulty effect on mean Task 2 RTs was as large as it was at the shortest SOAs in the first three experiments. Again, an answer is provided by the AEC models. Because of inherent variability in completion times for each stage of processing across trials of the PRP procedure, and because of participants' need to avoid inter-task response interference, some AEC models imply that a temporary strategic Task 2 response-selection bottleneck may be used on a subset of trials, yielding a small but positive Task 2 response-selection difficulty effect even at short SOAs (Meyer & Kieras, 1997a). Consistent with this implication, the variability in stage durations had less effect during Experiment 4 because participants did not have to deal with potential effects of response interference.

[9] As for Experiment 2, the decrease in the magnitude of the interaction between the effects of Task 2 response-selection difficulty and SOA from Session 2 to 3 of Experiment 4 cannot be attributed to a decrease in the amount of response-selection overlap between Tasks 1 and 2. Instead, the smaller interaction in Session 3 stemmed largely from the smaller Task 2 response-selection difficulty effect there. Specifically, as shown in Figure 11, the only change from Session 2 to 3 occurred for the Task 2 difficulty effect (it decreased by about 45 ms) at the 1000-ms SOA.

Another remaining question concerns why some past studies that have manipulated Task 2 response-selection difficulty did not find underadditive interactions with SOA effects on Task 2 RTs (Carrier & Pashler, 1995; Fagot & Pashler, 1992; McCann & Johnston, 1992; Pashler, 1984; Pashler & Johnston, 1989; Ruthruff, Miller, & Lachmann, 1995). Although our experiments offer no firm answer to this latter question, the present results and AEC models suggest some interesting possibilities. As stated previously, under certain task conditions, participants may need practice to develop optimal task-scheduling strategies. Many previous studies have collected data during only one session (Carrier & Pashler, 1995; Fagot & Pashler, 1992; Pashler & Johnston, 1989; Ruthruff, Miller, & Lachmann, 1995). Perhaps they would have produced underadditive interactions if participants had been given more practice. Additionally, in some studies, the longest SOA was shorter than the mean Task 1 RT (Fagot & Pashler, 1992; Pashler & Johnston, 1989; Ruthruff, Miller, & Lachmann, 1995). If Task 1 processes are still under way at the longest SOA, then a difficult secondary task may benefit from processing slack across all SOAs, thus reducing any underadditive interaction. This latter possibility is especially problematic because the effects of response-selection manipulations in some past studies have been very small (e.g., 50 ms or less; Pashler, 1984; Pashler & Johnston, 1989). With such small effects, the power to find an interaction is drastically limited (Sanders, 1980).

This leaves only the study by McCann and Johnston (1992) as a potentially informative test of the RSB hypothesis. They manipulated Task 2 response-selection difficulty using S-R compatibility during two sessions in each of two experiments, producing moderate difficulty effects over a wide range of SOAs (50 to 800 ms). However, neither of these experiments yielded a highly reliable interaction between the effects of Task 2 response-selection difficulty and SOA on mean Task 2 RTs.

Why did McCann and Johnston (1992) fail to find an underadditive interaction? There are several possible answers. In their first experiment, the mean RT for even the easy Task 2 was over 600 ms at the longest SOA. This secondary task required participants to respond to both the shape and size of a centrally presented visual stimulus. Perhaps these requirements induced participants to adopt a cautious task-scheduling strategy that two sessions of practice could not overcome. Nevertheless, the Task 2 difficulty effect was 17 ms less at the shortest SOA than at the longest. This underadditivity, which approached reliability [$F(3,69)=1.94$, $p<.15$], suggests that some response-selection overlap may have occurred even under this very difficult task condition. Fortunately, McCann and Johnston's second experiment used an easier secondary task, but unfortunately, participants had to make post-SOA eye movements to identify the Task 2 stimulus. Because Task 2 processing could not begin until the Task 2 stimulus fell on the participants' foveae, these eye movements effectively added 150-175 ms to the shortest SOA (Abrams & Jonides, 1988), thus eliminating much, if not all, potential processing slack (cf. Meyer & Kieras, 1997b).

When peripheral bottlenecks associated with eye movements are eliminated, our results show that concurrent response selection is possible under conditions that involve two different manipulations of response-selection difficulty. These data clearly support AEC models (Meyer & Kieras, 1997a, 1997b, 1997c; Meyer et al., 1995) whereby task performance is coordinated through adaptive executive control. The additional finding from Experiment 3 that response-selection difficulty effects change with practice leads to one important direction for future research. More studies are needed now to identify exactly what aspects of particular task situations (e.g., amount of practice, experimental instructions, type of training, etc.) encourage or discourage concurrent response selection on the part of human multiple-task performers.

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